ESTIMATING THE YIELD OF GRAIN FROM THE WEATHER

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"Weather", state J. B. Kincer and W. A. Mattice, of the Weather Bureau at Washington, in their Statistical Correlations of Weather Influence upon Crop Yields, "in the aggregate, for a given period of time as affecting plant growth, is a composite of many elements, such as temperature, rainfall, sunshine, wind, relative humidity, etc. Growing crops are influenced more or less by all these which, in combination with one another, make up the weather of the season." It is realized that there are limitations to the study of the influence of weather upon the growth and development of the wheat plant and other grains and finally the yield. This is owing to the fact that there is a large number of phases to each of the above elements. For temperature, for instance, there are the mean daily maximum, mean daily minimum, highest temperature, mean daily range, etc. Rainfall can likewise be subdivided into many phases. It is the writer's intention to confine himself principally to the total provincial monthly rainfall (average for a number of stations) and the mean daily minimum and maximum temperatures (average for the province).

Some investigators of this problem.—Among those outstanding agriculturists who have attempted to relate the yield of grain crops to the weather are Gilbert and Lawes, of the Rothamsted Experiment Station at Harpenden, England. Dr. E. H. Chapman, formerly of the Dominion Bureau of Statistics, himself a student of the subject, stated in his Forecasting of Crops from the Weather that in 1880 Gilbert and Lawes came to the conclusion that seasons of high production were preceded by a warm winter, a warm early spring, and a shortage of rain in winter and spring. As far as Canada is concerned this might apply to fall wheat and rye but not to spring crops with which we are dealing in this article. He also stated that Sir Napier Shaw, the eminent English meteorologist, in 1905 endeavored to calculate the yield of wheat in England, basing his estimates upon the rain of the previous autumn. Later, S. M. Jacob, of the Indian Meteorological Service, in a paper published in 1916, showed how in India even well-irrigated wheat liked a moist seed bed in September. In Japan, work has been done in forecasting the yield of rice. "It has been observed" stated Dr. Chapman, "that the success of the rice crop depended chiefly upon an even temperature and bright sunshine in August, cold at that season involving a failure." In Sweden, Alex Wallen found that there was a distinct relationship between rainfall and temperature on the the one hand, and the yield of the four cereals, wheat, barley, oats, and rye, for each of the 26 governments of Sweden in every month of the growing periods of these crops during 1881–1910, the period of his study. Then we have A. J. Connor, climatologist of the Dominion Meteorological Office at Toronto, who has made important contributions in the field of agricultural meteorology. The work of T. R. Blair in the United States should also be mentioned.[1]

Previous work on this problem.—In commencing this study the records of the different experiment stations in the West were examined. A series of charts were drawn, showing the inches of rain for the months of April to September; the minimum, the maximum and mean temperature; and also the hours of sunshine, for each year of the period 1918–27. The condition of the wheat crop as given by crop correspondents of the Dominion Bureau of Statistics at May 31, June 30, July 31, for each of these years was compared with the amount of rainfall and the temperatures for each month, and there was observed a relationship between the yield (as derived from the condition reports) and the variations in these two factors. In general, a favorable distribution of rain and even temperatures resulted in average or better yields, and this result was confirmed when the actual yield was forecast later in the season by crop conditions and threshing returns, other than the method we are about to describe. From this start, it was decided to select from the various records of meteorological data, those bearing most directly upon crop yields, such as we have already mentioned. In carrying out this idea, an experiment was made with the 1926 census of the Prairie Provinces, which dealt with the yields of crops for the year 1925.

The 1926 census of agriculture used as a basis of this study.—In this experiment, 50 areas lying close to as many meteorological stations in Saskatchewan were chosen. These areas were selected as representative localities in the Wheat Belt of this Province, as follows: *Qu'Appelle River region:* Arcola, Caron, Drinkwater, Imperial, Kamsack, Lunsden, Nokomis, Pilger, Qu'Appelle, Quill Lake, Seamans, Strasbourg, Whitewood, Yellow Grass, Yorkton. *South Saskatchewan region:* Assiniboia, Cadillac, Chaplin, Coulee, Consul, Gravelbourg, Haverhill, Hughton, Klintonel, Leader, Maple Creek, Outlook, Penant, Shaunavon, Swift Current, Vidora. *North Saskatchewan region:* Anglia, Biggar, Kindersley, Macklin, Meadow Lake, Prince, St. Walburg, Scott, Turtleford, Waweca, Witchekan. *Saskatchewan Forks region:* Dundurn, Harris, Kinistine, Melfort, Prince Albert, Rosthern, Saskatoon, Tugaske. These stations are selected from the four geographical regions of the Province. They were taken to represent the different climatic conditions, types of soil, etc. of the wheat region. The yield per acre of spring wheat for the year 1925 in each of these areas, or parts of census divisions, was calculated from the records of the census. These yields were then studied in connection with the total monthly rainfall, mean daily range of temperature, mean monthly temperature for each of the above stations and for each of the months April to September during 1925. An endeavor was made to discover, if possible, whether there was any relationship between the yield of wheat in each area with the rainfall in each month; that is, whether variations in the number of inches of rainfall corresponded with any differences in yield per bushel of spring wheat from one area to another. Besides these weather factors, other data contained in the census records, such as rural population per 1,000 acres, acreage of unimproved and improved land, percentage of land owned or rented, acreage under summer-fallow, spring and fall plowing, yearly expenditure upon equipment, etc., were studied as to their possible influence upon the yield of spring wheat. But it was found that these factors, other than those of the weather, could not be used in their available forms as having any direct bearing upon the yield, due probably to the presence of other unknown compensating factors whose effects could not be estimated.

[1] Thomas R. Blair. Partial correlation applied to Dakota data on weather and wheat yield, MO. WEA. REV., February, 1918, 46: 71-73. Temperature and spring wheat in the Dakotas, *ibid.*, January, 1915, 43: 24-26.

Variations in yield.—We discovered a wide variation in the yield per acre of spring wheat in these different areas. Our method has been to place the yield and the rainfall for each area and station alongside one another and to study the bearing which one has on the other, or whether a large plus or minus from the average difference in rainfall from one station to another is accompanied by a similar change in yield in the area contiguous to that station. If a definite relationship could be established between these two variables and other weather factors, and mathematically expressed, it would be quite possible to estimate the probable yield for subsequent years from the experience of the year we are studying. The difficulty, however, is in the wide variation in the amounts of rain which fall at each point in any month. By taking a period of years rather than a single year such as we already have done, seasonable differences are largely overcome by counterbalancing the effect of one season upon another.

Results of the study of the 1925 census.—For the purpose of preventing the accidental features of a single year which might occur, such as hail, early frost damage, insect injury, from in some measure hiding the results we have been trying to obtain, the average yield per acre of spring wheat for each of the above areas for the years immediately surrounding 1925, viz, 1923, 1924, 1926 and 1927, were also compared with the yields in each area for 1925 and with the meteorological data already mentioned. By suitable methods, a fairly high "total correlation" was obtained. This correlation seemed sufficiently high to warrant the belief that certain of the data could be used as a means of estimating the crop; its value was $R=0.80$, demonstrating the fact that, for the year 1925 in Saskatchewan at least, these various factors were closely related to yield. This, however, might not always be the case. For instance, if we had been enabled to gather data about the peculiarities of each area, that is, for instance, the average rainfall distribution for each month of past years, and the variations from the normal temperature, we might find that in some years the yield showed little relationship to the weather, due to the interference of other agencies such as hail, rust, early frost, etc. This coefficient, although amply sufficient to demonstrate the correlation between yield and the previously mentioned weather factors, was not considered of sufficiently high value to warrant its reliability for prediction. The next step, therefore, was to collect the data on yield and weather for a period of years to determine whether this method would give a higher relationship and be a surer means of estimating the yield from the weather data available.

Study of the period 1904–28 in Saskatchewan.—The differences from the average, or the variability in the crop yields already referred to, due to nature of soil, etc., which might be considered as existing between 50 areas would largely disappear when the Province as a whole was taken over a series of years. Changes in methods of culture, and different crop rotations, in the Province over this period would be slow; increases in yield due to improved methods of culture in some parts of the Province would be largely counterbalanced by the exhaustion of soil in other parts. To demonstrate the differences in yield (average for the whole Province), from one year to another and in the amounts of rainfall in comparison with a single year at different points, table 1 has been constructed:

TABLE 1.—*Yield per acre of spring wheat in Saskatchewan compared with rainfall of the growing period (April to July) for the years 1904–30*

Year	Yield per acre	Rainfall, April-July	Year	Yield per acre	Rainfall, April-July
	Bushels	*Inches*		*Bushels*	*Inches*
1904	17.5	6.43	1919	8.5	5.81
1905	22.3	7.67	1920	11.2	6.71
1906	21.4	9.55	1921	13.7	10.36
1907	13.5	7.10	1922	20.2	6.92
1908	13.6	8.08	1923	21.2	11.19
1909	22.1	11.15	1924	10.2	5.13
1910	15.5	6.75	1925	18.8	7.72
1911	18.5	10.24	1926	16.2	6.33
1912	19.9	9.46	1927	19.5	10.49
1913	19.5	7.32	1928	23.3	6.71
1914	12.4	6.17	1929	11.1	4.95
1915	25.2	8.97	1930	13.7	6.89
1916	14.2	11.07			
1917	14.2	4.74	Average 1904-30	16.6	7.78
1918	10.0	5.92			

An inspection of the above table shows that the variations in the yield of wheat and in the amount of rainfall for each of the years in question do not exactly coincide. For instance, in 1922 the yield per acre for the Province averaged 20.2 bushels and rainfall for the growing period over the Province 6.92 inches, while in the following season of 1923 the yield was 21.2 bushels per acre with a rainfall of 11.19 inches, which was well above average. It would be expected that a larger rainfall would produce a larger yield in 1923 than in 1922. We note from this table a number of seasons in which the rainfall was practically equal to the average of 7.78 inches, viz: 1905, 1913, 1925. But yields equal to, or nearly, the average of 16.6 bushels did not correspond with average rainfall. We do notice, however, that the years which had low rainfall, such as 1914, 1919, 1924, 1929, also had low yields, partly due to this fact along with other peculiar features of each season which we will refer to later and which make it difficult to secure a high relationship. Included in this study are the total monthly rainfall of the previous fall months of September and October, the total monthly rainfall for each of the current months of April to August, and the mean daily minimum temperature for the month of July. The total correlation (as explained before) between the yield of wheat for the preceding years and these meteorological data was $R=0.90$, higher than that obtained from a study of the yields and weather factors in the census year.

Study of the period 1914–28 for each of the three prairie Provinces of Canada.—The results of this second study, however, were not considered of sufficient value to warrant the making of an estimate. It became clear that the methods used in the collection of data between the years 1904–13 were different from those used after 1914 owing to an improvement in the manner of compilation by both the Provinces and the Dominion Bureau of Statistics. This was considered a strong disturbing element in obtaining satisfactory results from a study of the period 1914–28 either in Saskatchewan or the other two Provinces. In the study of yields, therefore, for the period 1914–28 in each of the three prairie Provinces, rainfall and temperature were studied in their relationship to one another. Included in this investigation were the previous autumn rainfall of the months August, September and October, the winter precipitation, (the months of November to March being included), the total monthly rainfall of the months of April to July, already studied in the former series, and the mean daily maximum temperature for July.

The rainfall of the above periods was found on analysis to vary directly with the yields when taken over the whole period. However, an increase in rainfall from one year to another did not always result in a corresponding increase in yield, but was often the reverse. Generally, however, yields over 15 bushels per acre, the average for the years 1914–28, accompanied average amounts of monthly rain of 4.0 or more inches in the previous fall, over 3 inches in June and in July. Exceptions from this, which occurred in our study, have been the reason for our taking up this work and making such a complete analysis of yields in each of the Provinces. With *regard to winter precipitation which has been included*, there was found to be a minus relationship between the yields of wheat in each of the Provinces under review and the amount of snowfall and rain during the winter months. This did not mean that the snowfall had no bearing or influence, but that its influence or effect was hidden by other factors, some of which have been referred to already. Experiments made at the experimental station at Swift Current, over a period of 7 years up to 1929, have discovered no appreciable increase in soil moisture from the snow cover of the previous winter. Whatever increase had taken place could be wholly ascribed to rains which penetrated the soil when the ground was in an unfrozen condition. Evidence to confirm this statement was available over an extensive area during the spring of 1928.

The results from our study for this period of 1914–28 of the yields of spring wheat in each of the three Prairie Provinces and the extent of its dependence upon the previous fall rain, previous winter precipitation, rainfall of growing months, and mean maximum temperature were considered quite satisfactory. Fairly high relationships were established when these factors were correlated with the average yields of spring wheat in each Province. The estimated yields obtained from this study were compared with the actual yields as compiled by the Bureau of Statistics and provincial governments. In many cases the expected yields were very close to the actual yields over this period, but for some of the years there was a difference due to causes in which the true relationship between the yield and rainfall could not be established owing to other factors or unknown agencies (or perhaps forces) being at work to offset the effect of the rainfall or beneficial temperature. A closer approximation between the estimated yield in Saskatchewan and the actual yield was secured than for the other two Provinces for the period of years used, although the variability or difference of the yields from the average was less in Manitoba than for either Saskatchewan or Alberta.

Additional meteorological factors.—Some of the forces which have rather counteracted the beneficial influence of rainfall or moderate temperatures during the growing period are soil drifting, insect damage, rust—these three take a large toll in some years, such as that by the rust epidemic in 1916. We have already referred to these factors as accidental features of a single year and for this reason we took a period of years for our study, and we have partly succeeded in overcoming this difficulty by obtaining a fairly high relationship or total correlation. Insect injury in a large measure is due to certain weather conditions. Soil blowing is partly due to dry weather and high winds. Rust is caused by wet weather and high temperatures and high humidity, besides the direction of certain winds which carry the rust spores. These, it has been thought, have been so intermixed with certain weather factors as to make it difficult to measure the degree of influence or "weight" exerted by the rainfall at any particular period.

Experimental farms of Canada.—Bearing in mind the importance of making a finer analysis of selected districts in each Province, similar to that of the 1926 census (only over a period of years), it was decided to make a study of the yields of not only spring wheat but also the other grains on the experimental farms. The nine farms and stations in western Canada included in this study are: Manitoba—Brandon and Morden; Saskatchewan—Indian Head, Rosthern, Melfort, and Swift Current; Alberta—Lethbridge, Lacombe, and Beaverlodge in the Peace River country. These stations were chosen not only for the reliability of their yield records but also for the reason of the rotation experiments on different ereael crops in connection with their response to certain environment, the combination of crops, fertilizing, and other cultural experiments. It is their response to environment with which we are concerned, as these are additional features in our study of the yield of cereal crops and the weather. This point has been investigated in our consideration of the yields of spring wheat at each of the 50 areas as influenced by fall plowing, spring plowing, summer-fallowing, etc. We were not able in our study of the census data, however, to establish any definite relationship between yield and these nonmeteorological factors. It is hoped in this study at each of the farms to find some connection between yield and the various methods of culture which can be reduced to a mathematical basis, such as we have endeavored to do in previous studies, in order to make an estimate of the yield.

A study is being made of the rainfall during the crop years at the experimental farms of Brandon, Manitoba; Indian Head and Scott, Saskatchewan; Lacombe, Lethbridge in Alberta, from the time these farms were started, up to the present time. The average maximum temperature for the current months of May, June, July will be related to the precipitation over each preceding crop year.

The "quotient" obtained by dividing the second factor by the first will be studied in relation to the yield of wheat and other crops. Mr. A. J. Connor, M. A., climatologist to the Dominion Meteorological Office at Toronto, has made a study of this, and very interesting results have been obtained by him for the districts surrounding the meteorological stations of Winnipeg, Calgary, Edmonton, Medicine Hat, Battleford, Prince Albert, Qu'Appelle, and Swift Current, in which records have been available since 1883. The "quotient" mentioned above has been compared to the periods in which minimum and maximum sun spots have occurred, and these again compared with the yields of spring wheat in the above areas. This study of additional stations will be especially valuable owing to the fact that severe droughts have occurred in the prairie Provinces during the last 4 years. (See Canada Year Book, 1933, pp. 47–59—Droughts in Western Canada, by A. J. Connor.)

A minute study of plant growth necessary.—In addition to studying yields in their relation to weather and other factors, already dealt with in detail, account must be taken of plant growth throughout the growing season. Its development must be carefully watched. Extensive soil-moisture experiments are being carried on at the Swift Current experimental station by Mr. S. Barnes, who is attached to the department of field husbandry of the experimental farms system. Much has been done to establish a relationship between the plant and factors connected with its growth. Evaporation is an important factor, in that the amount of water lost through this means might be greater than the amount of water received by the soil through rain, in which case a loss would occur in the available supply for the plant.

Evaporation.—By certain methods in use at the experiment stations the amount of water in the soil at seeding time is determined. At stated intervals the soil is weighed to determine the loss through evaporation. The difference between the initial and final weight each month indicates the water lost by the soil through evaporation and transpiration of the plants. It is stated that, as a rule, rainfall higher than average in dry climates results in yields higher than average, while in humid climates rainfall less than average usually produces yields higher than average. (Studies on yields and weather in other parts of Canada additional to that undertaken in the Prairie Provinces will be carried out in order to contrast the relationship in climates different from that of the west.) This might be partly due to less evaporation in humid climates; the supply of soil moisture thereby being more constant than in dry areas like that of southwestern Saskatchewan and in fact other parts of the prairies where the soil moisture is so rapidly depleted, and where abundant rains are at all times a necessity. Our study of the problem has convinced us that the rainfall is of prime importance. Unfortunately, however, data of sufficient amount to cover a great many more areas in the grain-growing regions of the west are not yet available.

Encouraging results, up to the present time, have been obtained and have led to the belief that the possibilities of estimating the yield of the various crops, based on the study of weather conditions of past periods, are very good. It will be quite possible, in fact, to make a prediction as to the outcome of the crop early in the season (in addition to the many reports on condition, based on averages) directly by taking the number of inches of rain at stated periods ("weighting" by proper methods) and from the above results making a calculation, in yield per acre, of the crop. Of course, the nonmeteorological agencies mentioned will be given consideration. The study of this problem, up to this point, has been the endeavor to establish some relationship between yield and weather, so that the various factors, principally rainfall and temperature, might be given certain values or weights in order to make, if possible, some calculation of the probable yield as compared with the actual yields reported by other methods now already established by the provincial governments, the Dominion Bureau of Statistics, and other agencies interested in the outcome of the crop, such as the grain exchange, the different wheat pools, Sanford Evans Statistical Agency, and the farming community in general.

Conclusion.—The important points which have been brought out in this article are, first, that rainfall, at certain periods of the year, is perhaps more important than at other times, depending on the crop that is grown. Our study has been on the yield of spring wheat in the prairie Provinces of Canada. Here we have investigated the yields both at several points in the Province of Saskatchewan for a particular year, namely, 1925, and over a period of years, namely, 1914–28, in each of the Provinces. We have brought out the fact that, of the two weather factors studied, rainfall and temperature, the first is the most influential. The way in which rainfall comes has a great deal to do with its usefulness. Showers during the growing period help the crop for a short time, but for storing water in the soil, showers of one-half inch or more are necessary. Then, the distribution of rainfall is very important. If the rainfall is of a torrential character, the rain falling at the rate of an inch or more per hour, the loss through run-off is serious. The summer-fallow is quite important and is partly for the purpose of controlling weeds and for storing moisture. Secondly, we have evaporation, which in many cases exceeds the amount of rainfall, so that the amount of soil moisture is lessened. Then, there are several other factors which are at work to reduce the yields besides lack of rainfall, such as lateness of seeding, poor cultural methods, poor seed, the wrong type of soil for a certain crop—although in this case well-distributed rainfall on comparatively poor soil might produce a good crop, while less than the average rainfall would result in a poor crop or none at all, as we have witnessed this past year in the West. Insect injury, plant diseases, and soil drifting are partly dependent upon moisture conditions as well as on temperature. It has been the endeavor of the writer to link up all these factors together over a period of years. The experience of past seasons has assisted in making some kind of a prediction of the crop. The successful solution of estimating yields, however, requires the cooperation of not only a specialist in statistics but also in agriculture and weather forecasting. It is planned to make an extended field study of crops over a period of years, and it is confidently hoped that a method will be found of accurately determining the yield of crops early in the season.

TIME LIMITS OF THE DAY AS AFFECTING RECORDS OF MINIMUM TEMPERATURE

By E. S. NICHOLS

[Weather Bureau office, Harlingen, Tex., July 1934]

Different methods of obtaining temperature records, especially variations in the time at which observations are taken, cause differences in the beginning and the end of the "day" for which temperature extremes are recorded. Thus, at regular Weather Bureau stations the daily maximum and minimum temperatures are recorded for the calendar day, midnight to midnight, local standard time, the data being taken from the station thermograms when the extremes are not shown by actual thermometer readings; while the recommended, though not universal, time for the once-daily observations at cooperative climatological stations is "about sunset"; and the maximum and minimum temperatures then read are recorded as belonging to the current day (on which they usually occur). At certain other stations, especially certain classes operated in some special services, as well as at some cooperative climatological stations, thermometers are read and set once daily in the morning, in many cases at 7 a. m. local time, or even earlier; and the minimum temperature then read is recorded as that of the current date, while the maximum-thermometer reading is, in published reports, set back to the preceding date, on which it almost always occurs. The early-morning readings are, at some stations, supplemented by additional afternoon settings of the minimum thermometer. Experience in different sections of the United States has shown that such differences in the periods taken as the "day" (even though each contains 24 hours) cause differences in the temperature records obtained; and questions arise regarding the frequency, amount, and importance of such variations in the records.